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Climate patterns derived from ocean wave spectra

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Key Points:
- We identify wave spectra data as a rich source of climate information
- A methodology based on wave spectral partitioning and wave spectral statistics is presented for exploiting these data
- Meteorological interactions of mesoscale phenomena are detected from the analysis of the local situation

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Abstract The fact that ocean surface waves are an integrated effect of meteorological activity has the interesting consequence that the memory of the wave systems is larger than that of the wind and storms that generated them. At each single point the related information is stored as its wave spectrum, a matrix containing the energy distribution of wave systems with different origins in space and time. We describe the concept of spectral partitioning and the technique used to obtain spectral statistics, whose outcome we associate with the physical reality. Using long series of spectral data we derive information of the, possibly very far, generation zones climatologically connected at a confluent point. Working on the eastern equatorial Pacific we focus on the prominent effects of El Niño events, for which interactions of mesoscale phenomena are revealed from the analysis of the local situation.

1. A Source of Information

The atmosphere and the ocean interact via the sea surface. While the fluxes (energy, matter, heat, etc.) through the surface are in a way a transient phenomenon, the macroscopically evident effect of wind waves has a longer memory. Once generated, waves bring the stored, limited but still useful, information at great distance, with some loss of information on the way. Our aim is to show how not only meteorological but also climatological information can be derived a posteriori with a suitable knowledge of the wave conditions even at a single location. To achieve this, a detailed characterization of the wave conditions is required. Most of the times these are summarized into the classical integrated parameters (significant wave height, H_s; mean and peak periods, T_m and T_p; and mean direction θ_m). However, state-of-the-art wave description provides us the full information stored in the wave spectrum, which contains the structure, in space and time, of the meteorological forcing.

Since its first appearing in the literature [*Pierson and Marks*, 1952] the concept of spectrum has revolutionized the mental approach with which we look at ocean surface waves. From the idea of a confused state with possibly dominant period and direction we suddenly realized that the sea surface could be conceived as a superposition of single sinusoidal waves. The step from a superposition of the single spectral components to the one of superposition of the related dynamical processes was a short one, and soon after, theories of generation, dissipation, resonant interactions, and bottom interactions, rapidly followed [*Pierson et al.*, 1955; *Phillips*, 1957; *Miles*, 1957; *Hasselmann*, 1962, 1974, among others]. Notwithstanding the implied simplification, the concept of a wave spectrum turned out extremely useful, one of its most important implications being the development of wave spectral numerical models and modern wave measuring techniques (see a summary in *Cavaleri et al.* [2007]).

Taking into account the implicit limitations (e.g., assuming a quasi-monochromatic swell propagating in homogeneous and stationary ocean and neglecting the effect of currents), the information stored in a sequence of wave spectra allows to derive for each wave system (soon to be defined) not only data about the wind speed and duration that generated it but also about the related time and position. Hence, if long series of wave spectra are available at one position, substantial information can be derived about the climatology of the generation areas. In this paper we apply this approach to a sensitive location of the eastern equatorial Pacific Ocean to show the results that can be derived. When regarded from a local perspective this area appears dull, with low wind and wave activity. Wave spectral analysis reveals that this is an area of confluence of wave energy generated in remote areas. We focus on two extreme periods related to El Niño phenomenon (1982–1983 and 1997–1998), whose large anomalies allow to visualize more clearly the interactions in these generating zones.

To illustrate the use of the spectral wave data, the proposed methodology, and our findings, first (section 2) we describe how the spectral information is handled via the partitioning technique and which data we have

used. Then in section 3 we identify the area to work on, its characteristics, and our basic climatological results. All this is summarized and commented upon in the final section 4.

2. Wave Spectra Partitioning and Long-Term Statistics

2.1. The Partitioning Technique

Waves generated by a certain wind are never monochromatic but distributed on a range of frequencies and directions forming energy clusters in the spectral domain (wave systems). An example is given in Figures 1a–1c. More frequently especially in the ocean, waves generated by different meteorological events, in space and time, reach together a certain location and the spectrum then appears as in Figures 1d–1f and 1g–1i, with two and three wave systems, respectively. The spectral characteristics of the wave systems depend on the generation conditions. If generated far away energy disperse on the way such that its spectral distribution is concentrated in a small domain and its characteristic frequency is comparatively low (swell). If generated locally, energy occurs in a larger range of frequencies and directions, the spectral distribution is broader, and its characteristic frequency is higher (wind sea). Following this principle, we can identify all energy clusters in a spectrum, associate them to different meteorological generating events, and derive some information about its genesis. This is achieved via the so-called partitioning technique, described in detail in *Portilla et al.* [2009].

For long series of spectra data, partitioning has the main advantage of facilitating the analysis of individual wave systems independently from others. For instance their time sequence allows to determine how far those waves come from. Granted the known direction, we can estimate their generation area. An example is given in Figure 2a where we show the geographical distribution of the estimated source points in the Pacific Ocean. In Figure 2b the reference location is indicated. Another advantage of spectral partitioning is data reduction. Since a spectrum has a relatively large amount of information (order of 10^3), this can be achieved by summarizing spectral information into its basic parameters (e.g., energy, frequency, and direction) per wave system, reducing the volume of data of 2 orders of magnitude with a limited loss of information. As addressed in *Portilla et al.* [2015b], several approaches exist nowadays pursuing this aim. Here we advocate for the strategy of reducing the volume of data while preserving the relevant information. This is at the core of the spectral statistics techniques, in particular of the one presented below.

2.2. Wave Spectra Statistics

Using spectral decomposition via partitioning, each one of the wave systems seen in Figure 1 can be summarized by a few integral parameters (e.g., H_{m0}, f_p, and θ_p), corresponding to a single information in the (f,θ) space. The further step to derive spectral statistics consists in analyzing the resulting long-term distribution of these parameters. Specifically, again in the (f,θ) space, the bivariate occurrence distribution of the single original (f_p,θ_p) peaks is found to be a quite skillful descriptor of wave spectra realizations. This technique is described in detail in *Portilla et al.* [2015a]. An example of this distribution is shown in Figure 2c. Note that although appearing as a spectrum, this is now the statistical distribution of the various peaks (f_p,θ_p) from the spectral conditions at one locality along many years. The interpretation is straightforward. We see immediately which are the dominant systems in terms of recurrence. In Figure 2c there is of course no information about time (it is a long-term statistics) or about the energy of the systems (but this information is stored for later use). The contours and colors now represent how frequently each system appears. The main assumption then is that wave events with similar spectral, hence physical characteristics, group themselves into clusters in terms of their occurrence (Figure 2c). Long-term realizations guarantee the detection of these clusters, which are the basis for the definition of wave systems in a statistical sense. The key argument in our analysis is that this function summarizes the whole set of physical characteristics of the waves reaching the area. Since these characteristics are unique at every site, this distribution constitutes a sort of fingerprint of the local wave climate. Identifying these populations is straightforward by using the same partitioning algorithm as for a single spectrum. For our reference point, and for the present purpose, we identify the four main wave systems (WS) indicated in Figure 2c as WS1, WS2, WS3, and WS4. The interpretation of this information in the context of the local meteorological and wave conditions of the region is given in section 3.

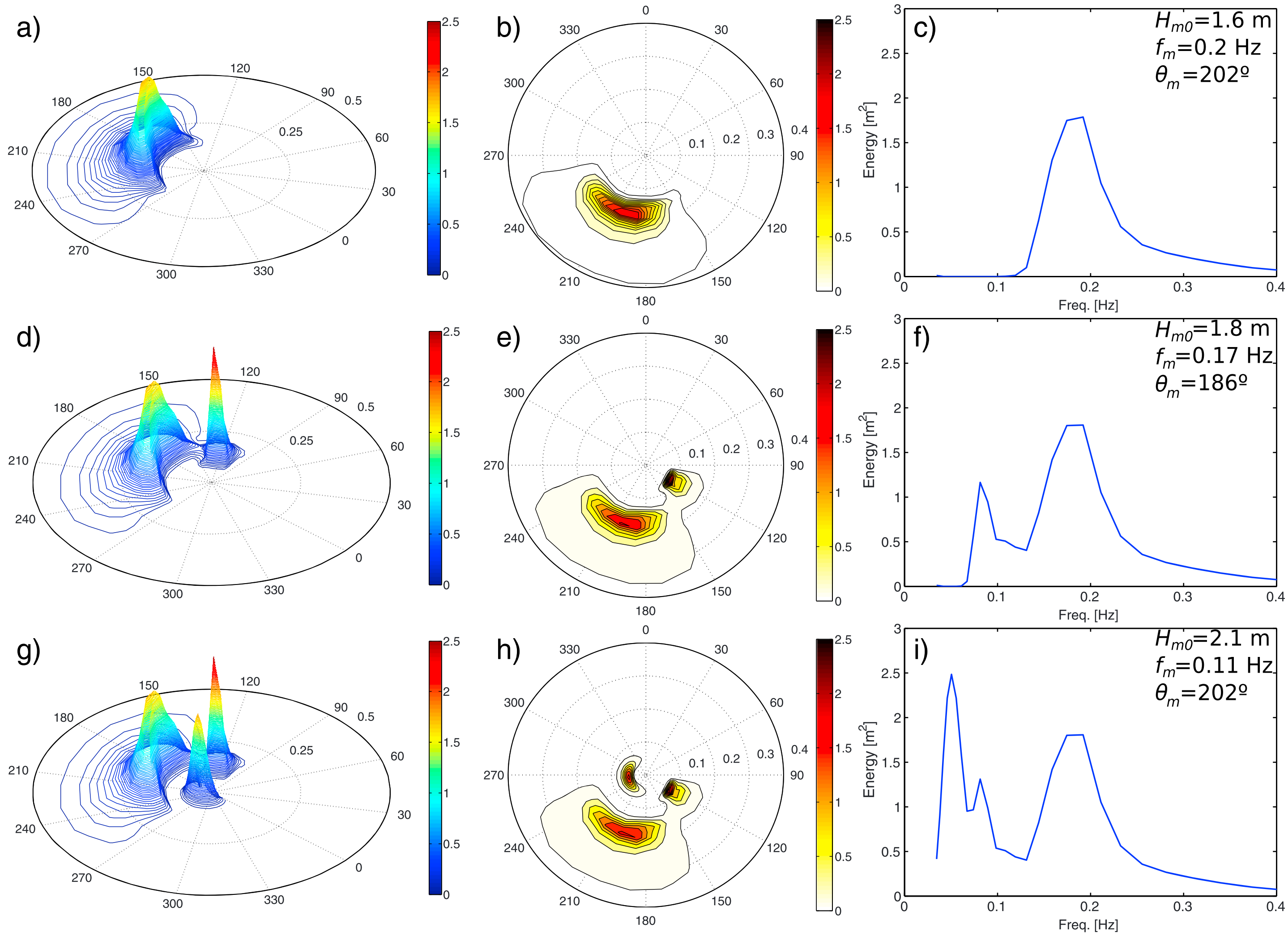

Figure 1. Example of unimodal, bimodal, and multimodal spectra illustrating the loose physical meaning of integral parameters in wave description for multimodal states.

2.3. The Data We Have Used

It is clear that for our analysis we need long time series of 2-D spectra at one specific location. There are two obvious lines of action, measured and model spectra. In principle, measured spectra may sound as more attractive. However, there are two main limitations: (1) the discontinuity of the data in space and time, from the buoys (or similar point measurements) because available only at a limited number of points and from satellites because continuously varying in time and position, and (2) most of them do not extend much in the past.

Given the reliability of the present meteorological and wave models, especially on the large expanse of the oceans, with full spectral availability in space and time (see, e.g., the statistics of the European Centre for Medium-Range Weather Forecasts, Reading, UK, at www.ecmwf.int), their use appears as the most convenient solution. Further, the long-term spectral signatures obtained from these data have been found consistent with those from a 3 year local buoy record. Granted the different nature of the two data sources and their inherent uncertainties and limitations, they both show the main four wave systems described in section 2.2 with consistent spectral properties [see *Portilla et al.*, 2015b]. Given the climate perspective of the present study we have used model data from the ERA-Interim reanalysis database [*Dee et al.*, 2011]. They cover the period from 1979 until present on a reduced Gaussian grid with about 110 km spatial resolution. The spectra are available at 6 h interval, making for one point a total of more than 54,000 spectra with a 30×24 resolution in (f-θ) space.

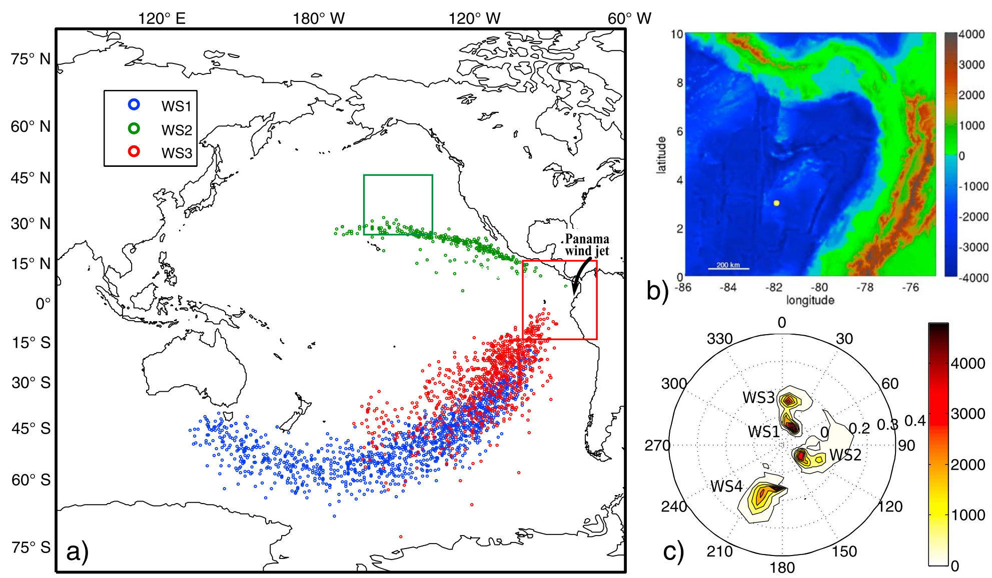

Figure 2. Study area and wave conditions. (a) Swell originating point sources for several events in the record. WS1 is marked in blue, WS2 in green, WS3 in red, and WS4 is represented with a black arrow. Their origin location is estimated based on the dispersion relationship [see *Portilla*, 2012]. (b) Zoom on the specific area showing the geographical and orographic details. The dot shows the position of the analyzed spectra. (c) Empirical probability density distribution of spectral partitions at the reference point (3°N, 278°W).

3. Analysis and Results

3.1. The Local Situation

As shown in Figure 2 our area of interest is the eastern equatorial Pacific, chosen, as we will see, as suitable for climatological consideration. This area is crossed by the Intertropical Convergence Zone (ITCZ), characterized by low to moderate wind speeds. Along the year, the ITCZ migrates from north to south (or vice versa) driving the local weather seasonality [e.g., *Mitchell and Wallace*, 1992]. Wind activity is mainly due to two distinct mesoscale meteorological forcing. The first is due to southerly trade winds intruding into the Northern Hemisphere with typical flow directions NW, N, or NE, depending on longitude. These are associated to the austral winter activity. The second is due to the pressure gradients between the Caribbean sea and the Pacific Ocean, driving the well-known wind jets in Central America [*Chelton et al.*, 2000]. These wind jets are favored by the orography of the isthmus (shown in Figure 2b), characterized by gaps in the mountain range at Panama, Papagayo, and Tehuantepec, that allow winds to flow through. The chosen point is affected primarily by the Panama wind jet.

The area is affected by the El Niño phenomenon, whose main regional symptoms are the increase in sea surface temperature and the reduction of wind speeds [*Wyrtki*, 1981; *Rasmussen and Carpenter*, 1982]. El Niño is also associated to local enhanced precipitation in the continent, taking place usually around the month of December. Nowadays, it is recognized that El Niño affects the whole Pacific Ocean and even the whole Earth over a period that extends several months. In the last decades there have been two extreme and distinctive El Niño events, one in 1982–1983 and the other in 1997–1998. Other anomalous years are sometimes also associated to El Niño; however, their reported effects are not always clear nor consistent.

As for waves, conditions are dominated by swells arriving from remote areas in the north and south hemispheres. The position in Figure 2b is fully open to the Pacific waves, with the exception of shielding from the north and north-west directions by the Central America isthmus and Mexican coastline. As evident from Figure 2c, the surrounding area is characterized by the four wave systems, named WS1, WS2, WS3, WS4. Briefly summarized, WS1, flowing mainly to 40°, has far origin in the storm Antarctic belt in the Southern Pacific (see Figure 2a) till as far as Australia and New Zealand (remember the famous paper by *Snodgrass et al.* [1966]). WS2, flowing to 120°, is associated to North Atlantic storms in a belt between 15°N and 30°N. WS3 flows in the same directional quadrant of WS1 (10°), but the higher characteristic frequency (Figure 2c)

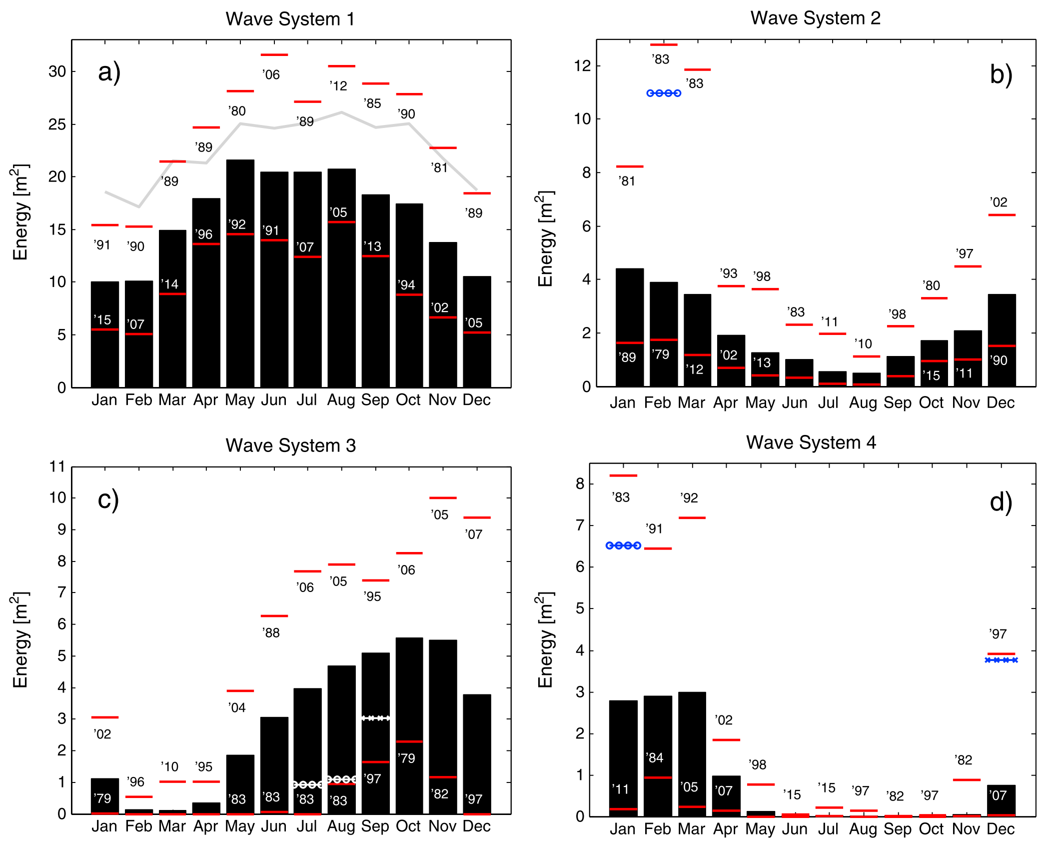

Figure 3. (a–d) Seasonal characteristics of the four main wave components in Figure 2c. The continuous gray line in Figure 3a indicates the overall energy. The horizontal red segments indicate the extreme values and the corresponding year. The circles (blue) indicate the 1997–1998 events. The crosses (blue) indicate the 1982–1983 events.

and the rate of change, in time, of the frequency peak in the single events identify a closer source. WS4 is connected to the Panama jet [see *Portilla et al.*, 2015b].

3.2. Climatological Connections

An advantage of the method of spectral partitioning compared to overall integral parameters (H_{m0}, $T_{m-1,0}$, and θ_m) is that it makes possible the independent analysis of the different wave components. Figure 3 shows the integrated monthly energy content for the four systems. The *y* scales in the four panels are different to favor the visualization of the variability of each wave system. In each panel the minimum and maximum values for each month are also shown, indicating the year in which they happened. Figure 3a shows the distribution for WS1, marked seasonally by the winter activity of the austral hemisphere, varying up to 50% from winter to summer. Its energy is relatively high also in the austral summer months and, in general, higher than the other wave systems as shown by the gray line indicating the total energy of all the systems. Because of the different magnitudes of the four components the total signal displays basically the trend of WS1, only smoothed by the sequence of the others. In fact, WS1 and WS2 are completely out of phase to each other. WS3 peaks in October progressively increasing from May to January, out of phase with WS4 that peaks in March. Anticipating one of our conclusions, we point out how the analysis of the separated signals reveals known climate features like the interannual passage of winter (hence stormy season) between north and south. We can also note the dominance of the austral meteorological activity in the southern Pacific Ocean that regulates the location of the Intertropical Convergence Zone (ITCZ) above the equator [e.g., *Harries and Belotti*, 2010; *Hellerman and Rosenstein*, 1983].

For a hint on the possible more climatological interpretation of these data, it is convenient to plot in Figures 4a–4d, the long-term history of the monthly averaged energy for each of the four identified wave

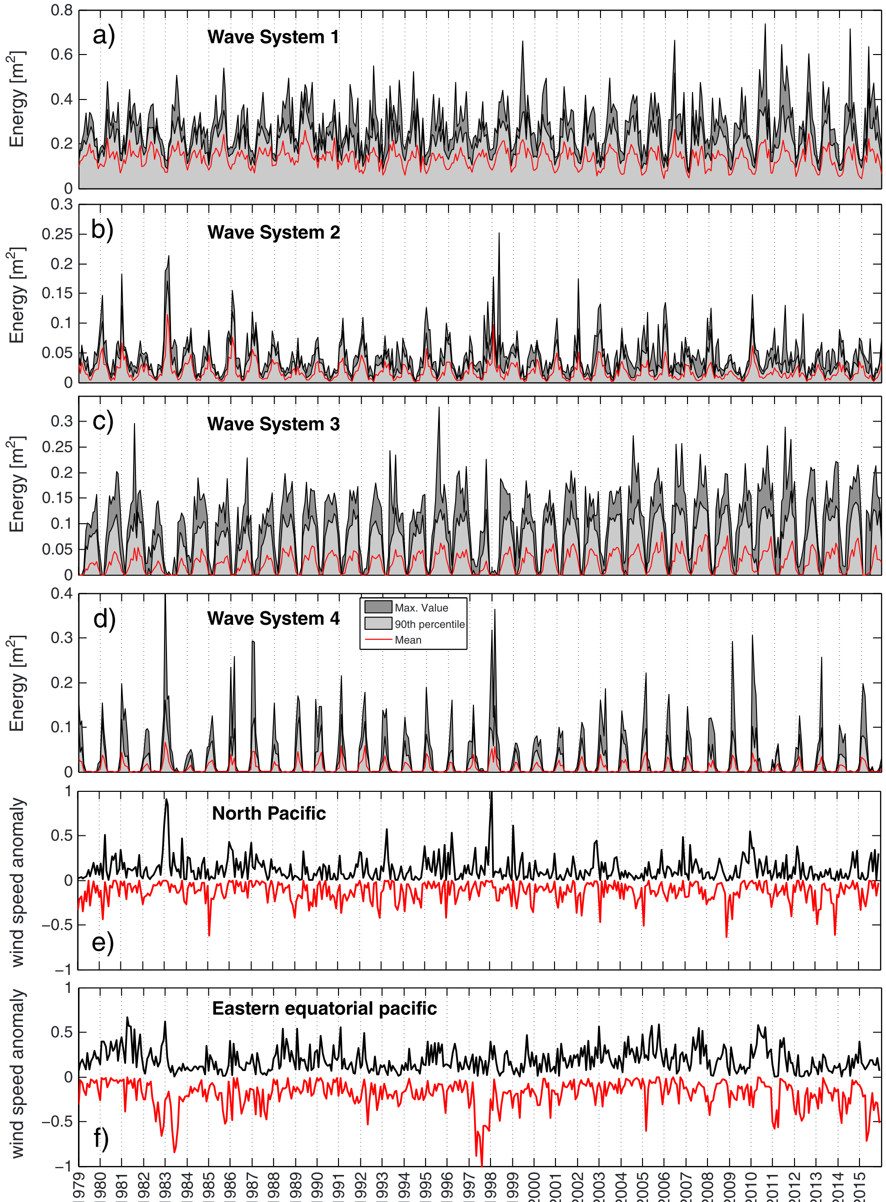

Figure 4. (a–d) Time series of monthly average energy for each of the four wave systems (see Figure 2) identified at the reference point. (e and f) Average monthly positive and negative wind speed anomalies at all the grid points in the two areas marked in Figure 2a: 15°S–15°N, 70.5°W–99.75°W (Figure 4e); 27.0°N–45.0°N, 135.0°W–159.75°W (Figure 4f).

systems. Apart from an expected year-to-year variability, two periods show what could be defined as anomalous behavior, the two sequential years 1982–1983 and 1997–1998, with strong positive anomalies for WS2 and WS4, and negative ones for WS3. These are both El Niño years, actually particularly strong [see *Wolter and Timlin*, 1998]. It is naturally tempting to associate these independent data sources exploring first the physics that connect the related physical parameters, then which useful climatological indications are possible to derive from the apparently simple, but actually rich, wave spectra source of information.

The stronger WS2 and WS4 (see Figure 2) may imply enhanced meteorological activity in the Northern Hemisphere, respectively, in the extratropical North Pacific and in the Caribbean Sea. The former one has been verified plotting (Figure 4e) the positive and negative wind anomalies in an area representative of the generation of WS2 (box between 27.0°N and 45.0°N and 135.0°W and 159.75°W in Figure 2a). Showing separately positive and negative anomalies helps to better grasp the dominant effect in the area. While the negative values are irregularly distributed, the two dominant peaks in El Niño years are clear outliers,

strongly indicative that something special was going on. This suggests a more southern action of the northerly storms with a possible southward shift of the ITCZ.

The higher energy of WS4 during strong El Niño years requires a different justification. Rather than extended in time, the large energy of this system is associated to large single robust meteorological events in North America and the Caribbean Sea. The complex interactions in this area between the Atlantic northeasterly storms, the northwesterly stream over North America, and the easterly flow in the Caribbean Sea create many possible scenarios. During strong El Niño years the typical anticyclonic behavior of winds in the area seems to be disrupted causing an enhanced anomalous southward flow over Central America and across the isthmus. Granted that the detected effects point to connections outside the target area, we consider this as a typical example where a local effect encourages to consider more general causes/patterns that of course require a more extended analysis.

Similarly to WS2, we have verified the negative anomaly of WS3 in El Niño years by plotting the wind speed anomaly in an area related to active WS3 generation. The box, between 15°S and 15°N and 70.5°W and 99.75°W, is shown in Figure 2a. The resulting anomalies, both positive and negative, are shown in Figure 4f. Again, we find a perfect correspondence with the spectral data, the negative anomalies being also distributed over several consecutive months. Looking at the time series of the individual processes (Figure 4), we observe that the three presented anomalies are not simultaneous. A large negative anomaly of WS3 is followed by enhanced activity in the Northern Hemisphere in the periods of 1982–1983 and 1997–1998. While this may appear as obvious given that WS2, WS3, and WS4 have different seasonal patterns (see Figure 3), the link between these three processes becomes clear only via the analysis of the separated time series.

In spite of being the dominant system, WS1 does not show appreciable anomalous patterns during strong El Niño years. However, a possible, although vague, correlation is found for the 1989–1995 period, when very large WS1 values have been found for specific months (see the year of the maxima in Figure 3a). This is the period when, according to the Multivariate El Niño Index [*Wolter and Timlin*, 1993], there was a moderate, but extended, El Niño regime. Independently of this vague correlation, the dominance of WS1 in the total signal (as indicated in Figure 3a) highlights the importance of the partitioning approach because if the wave data were analyzed in terms of total integral parameters (as traditionally done [e.g., *Fan et al.*, 2016]), the information carried by the other components would be neglected. Moreover, although there are other essential and possibly sensitive variables (e.g., frequency and direction), here the analysis is focused on energy because it is the one displaying largest variations. A more complete analysis should include other variables as well.

In spite of the extended time during which El Niño has been scientifically studied, there is still debate about its precise causes and, more so, its implications. *Becker* [2016], although at a didactic level, provides a good picture of the present related knowledge and forecast capability. As wave men, tiptoeing in this much wider subject, we have been wondering about the role of waves in mixing the upper layer of the ocean. We are not talking about white-capping, the surface breakers in a windy sea, which act only on a depth similar to the wave height. We refer to the vertical mixing [*Babanin*, 2006; *Qiao et al.*, 2016] associated to the orbital motion within the wave action range, deeper in the sea the longer the waves. The fact that wave systems show an El Niño-related behavior can be suggestive of a consequence, but also of a, albeit remote, cause.

4. Summary and Discussion

The concept that the atmosphere and the ocean constitute, and should be considered as, a single system has now been accepted by the meteo-oceanographic community. Indeed, this is the obvious approach for any consideration on climate. Atmosphere and ocean interact via the sea surface, which, depending on the process, may retain a memory of the interactions. This is the case of wind waves that carry the message along large distances. Different messages may and usually reach a position at the same time. Based on this idea, the problem we have discussed in this paper is how to exploit the information contained in the wave spectrum. This has been achieved by using spectral partitioning techniques and the following spectral wave climate characterization, which allows us to define the local wave systems in statistical sense. The long-term signature of the wave spectrum is unique at every site and informative of the wave, hence meteorological, climate patterns. We have found interesting and instructive that the information stored at a single point is capable to provide quantitative indications about multiple far zones. While the mechanism of wave generation by wind makes this appear as obvious, the remarkable point is the capability of singularly distinguishing the multiple influences. We stress that the more traditional use of only wave-integrated parameters does not allow this capability.

While our target here has mainly been to present a methodology, some comments can be done on the reported results. We have shown how the analysis of wave spectral components offers a comprehensive understanding of the synoptic situation that may immediately hint to general trends and anomalies. At the study area, the analysis has revealed the presence of four main wave systems with widely spread generating. Long distance swells from the south hemisphere storm belt (WS1), swells from the North Pacific Ocean (WS2), a more closely generated system from the south-west Pacific (WS3), and locally generated waves due to wind crossing the Panama isthmus (WS4). The seasonal variations of these components point to several features of the Pacific climate. The dominant role of the southern wave activity (WS1) hints to the northward position of the ITCZ that in turn is related to the asymmetric balance in heat and meteorological input between north and south [e.g., *Harries and Belotti*, 2010; *Hellerman and Rosenstein*, 1983; *Hoskins and Karoly*, 1981]. The migration of the seasons between north and south is implicit in the sequence WS1-WS3-WS2-WS4 (Figure 3). These known features are relevant in that they demonstrate the consistency of the methodology.

Although only as a possible line of thinking, we have pointed out how the different character of some wave systems during El Niño periods could be interpreted as a consequence, but, given the critical feedback in the system, also as a possible contributing cause.

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